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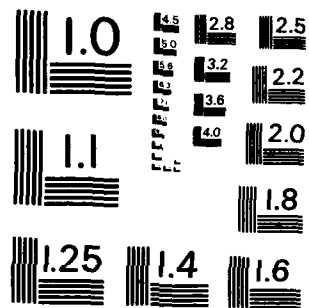
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The crest and upper slopes of the anomalous block are capped by shallow-water reef limestones. Determination of paleofacies and ages of samples of these limestones suggest that:

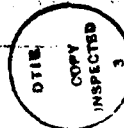
(a) The crest of the anomalous crustal block reached sea level and was exposed subaerially in middle Pliocene time, about 3 m.y. ago, and subsequently sank to its present depth at an average rate of about 0.3 mm/year, that is, a rate one order of magnitude faster than that predicted by the thermal contraction model for crust of the same age.

(b) The anomalous block reached at or above sea level, either continuously or intermittently, throughout the late Miocene, from roughly 10 m.y. ago.

(c) Paleocene sediments dated at about 58-55 m.y. have been recovered from the uplifted block where, assuming a spreading rate of 1.1 cm/year, the crust should not be more than about 35 m.y. old.

Vertical crustal movements at the Vema transform provide an example of vertical tectonism in the large oceanic transform/fracture zones.

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Research Papers

VERTICAL CRUSTAL MOVEMENTS AT THE VEMA FRACTURE ZONE IN THE ATLANTIC: EVIDENCE FROM DREDGED LIMESTONES

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ABSTRACT

Bonatti, E., Sartori, R. and Boersma, A., 1983. Vertical crustal movements at the Vema Fracture Zone in the Atlantic: evidence from dredged limestones. *Tectonophysics*, 91: 213–232.

A crustal block, shallower by over 3 km than the level predicted by the thermal contraction model for the ocean crust, is located on the southern side of the Vema transform in the Atlantic. Lithology, magnetic and gravity data suggest the anomalous block is an uplifted piece of crust and upper mantle, and not a constructional volcanic feature.

The crest and upper slopes of the anomalous block are capped by shallow-water reef limestones. Determination of paleofacies and ages of samples of these limestones suggest that:

(a) The crest of the anomalous crustal block reached sea level and was exposed subaerially in middle Pliocene time, about 3 m.y. ago, and subsequently sank to its present depth at an average rate of about 0.3 mm/year, that is, a rate one order of magnitude faster than that predicted by the thermal contraction model for crust of the same age.

(b) The anomalous block reached at or above sea level, either continuously or intermittently, throughout the late Miocene, from roughly 10 m.y. ago.

(c) Paleocene sediments dated at about 58–55 m.y. have been recovered from the uplifted block where, assuming a spreading rate of 1.1 cm/year, the crust should not be more than about 35 m.y. old.

Vertical crustal movements at the Vema transform: provide an example of vertical tectonism in the large oceanic transform/fracture zones.

INTRODUCTION

Some of the large oceanic transform zones are the locus of intense vertical tectonic motions of crustal blocks (Menard and Atwater, 1969; Dewey, 1975; Bonatti, 1978; Bonatti and Chermak, 1981) resulting in marked topographic anomalies relative to the age/depth relationships predicted by models of lithospheric thermal contraction (Sclater et al., 1971; Trehu, 1975).

The Vema transform offsets the mid-Atlantic Ridge (MAR) axis of some 320 km at about 11°N in the Atlantic (Fig. 1). A prominent topographic anomaly (trans-

verse ridge), the summit of which lies less than 600 m below sea level (Figs. 1 and 2), has been recognized on the southern side of the transform valley (Van Andel et al., 1967, 1971). A study of limestones recovered from this uplifted crustal block has indicated that its summit reached to sea level some time in the past, and has since subsided to its present depth (Bonatti and Honnorez, 1971; Honnorez et al., 1975).

Additional samples were recovered from the Vema uplifted crustal block during LDGO cruise RC21/04, with the aim of obtaining more information on the rates, mechanisms and causes of its vertical motions. The results of studies of these new samples, and their bearing on the problem of vertical tectonism at the Vema Fracture Zone and in oceanic transform zones in general, are discussed in this paper.

LIMESTONES FROM THE VEMA FRACTURE ZONE

Table I summarizes data on the dredge hauls obtained from the transverse ridge on the southern side of the Vema fracture valley during cruise RC21/04. Location of each dredging site is shown relative to a 1:1 topographic section across the ridge in Figs. 1 and 3.

At several stations near the summit and on the south-facing slope of the anomalous crustal block, limestones were recovered (Fig. 3). Most specimens had fresh broken surfaces; moreover, dredging operations were characterized by sharp bites and frequent anchoring. Both these observations suggest that the limestones we recovered are generally from "in situ" outcrops and not from loose rubble. What follows is a description of these limestones, with emphasis on their age, depositional environment, and post-depositional diagenesis.

Station RC21/04-2

Hand specimens: Several chunks up to some tens of centimeters across of pink to light red carbonate chalk.

Samples 2, 2D, 2H

Textures: Reddish biomicrites containing planktonic foraminifera, and occasional floating fragments of glass and basalt, which are often irregular, elongated and angular.

Structures: Scattered burrows and borings filled by darker plankton-bearing micrite.

X-ray Diffraction Mineralogy (XRD): Low-Mg calcite (< 1 mol.% MgCO_3). This and the following X-ray diffraction carbonate analysis have been made according to Goldsmith and Graf (1958).

Foraminiferal fauna: Samples contain poorly preserved planktonic foraminifera and few benthics. Species include: *Catapsydrax dissimilis*, *Globoquadrina venezuelana*, *Globoquadrina* cf. *altispira*, *Globigerina* cf. *praebuloides*, and *Globigerinoides subquadratus*. Faunas scraped from cavities within sample 2 include badly preserved specimens mainly of benthic foraminifera, cibicidids, gyroidinids, and large nodosarids as well as a few planktonic foraminifera including *G.* cf. *venezuelana* and *Catapsydrax* spp.

Age: Planktonic foraminifera are early Miocene in age, from the N4-N6 zonal interval (Berggren, 1972) about 23-18 m.y.

Environment: The foraminiferal oozes and the bathyal benthic foraminiferal generic associations along with the large nodosarids, which are typical of the bathyal zone, indicate open marine deposition at probably middle to upper bathyal depths on an isolated topographic high.

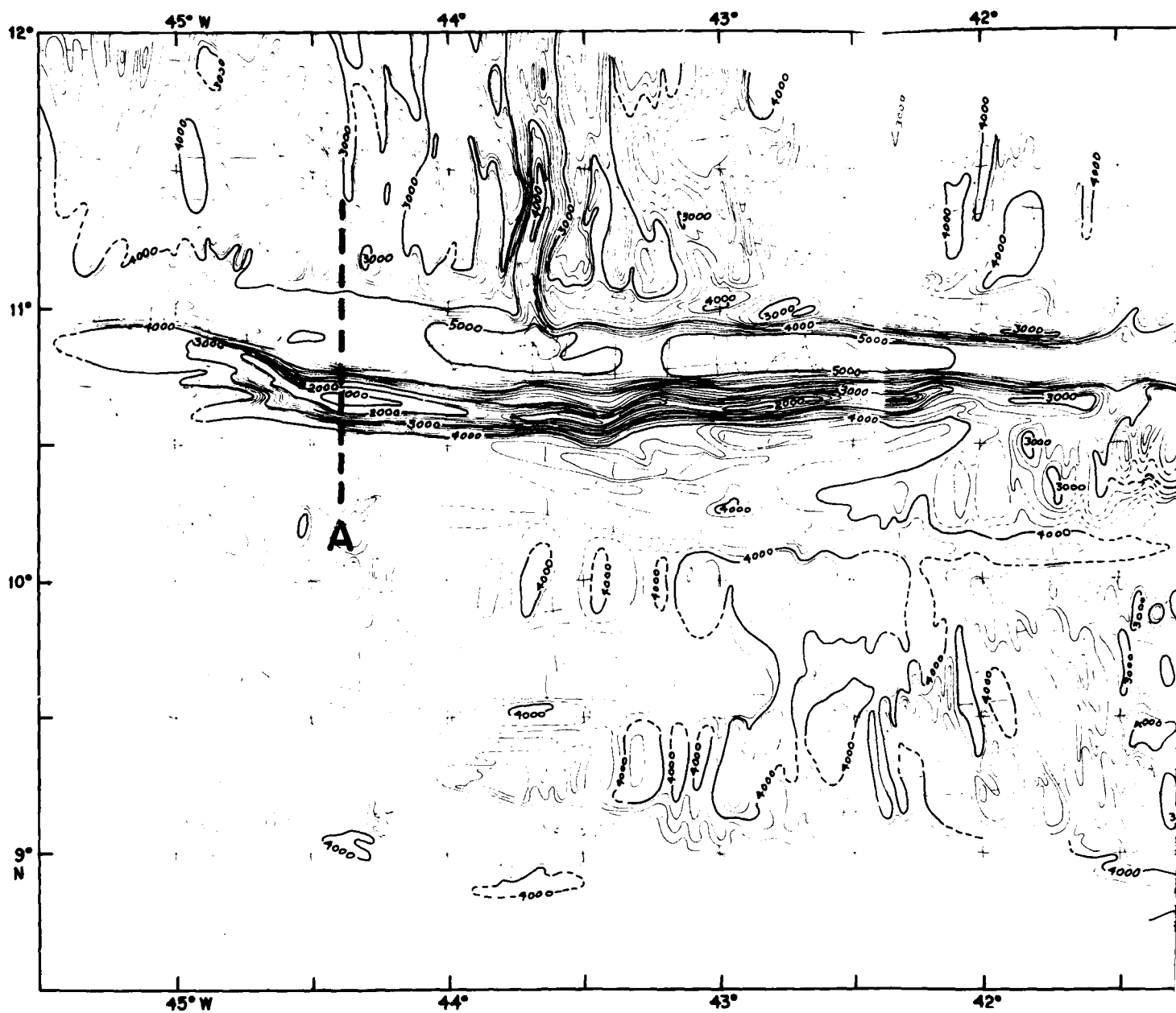
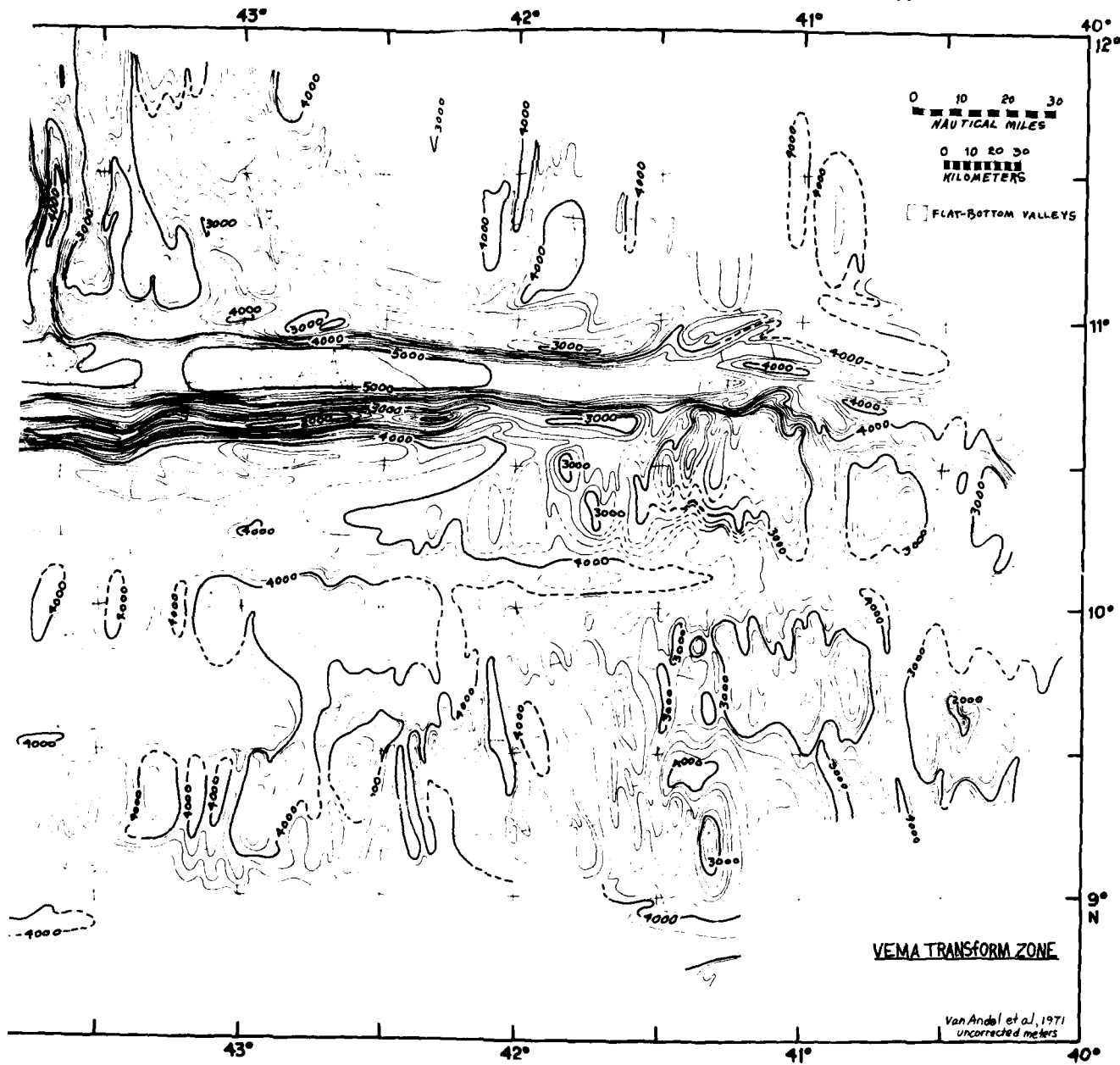


Fig. 1. Morphology of the Vema transform/fracture zone, from Van Andel et al. (1971). The anomalous topographic high on the southern side of the transform valley reaches its shallowest depth (~ 600 m below sea level) along profile A.



Van Andel et al. (1971). The anomalous topographic high on the southern side of the level) along profile A.

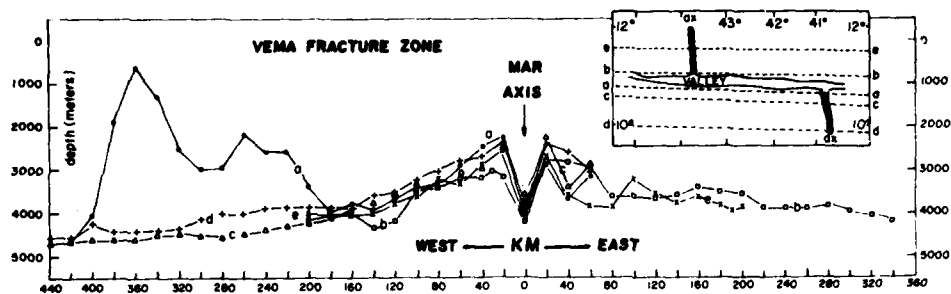


Fig. 2. Basement depth versus distance from accreting ridge segments in profiles immediately north and south of the Vema transform and parallel to it. Note the large positive anomaly in profile A, immediately south of the transform, while the other profiles approach those predicted by the thermal contraction model.

Sample 2G

No thin sections were made from this sample due to its bulk poor consolidation.

Foraminiferal fauna: Scrapings from the outer edges of the sample contained planktonic foraminifera such as pink-pigmented *Globigerinoides ruber*. Scrapings from a cavity within the specimen contain poorly preserved planktonic foraminifera (Fig. 4) which resemble the late Paleocene small thinly-keeled morozovellid. *Morozovella pusilla* as well as *Chilogumbelina* spp. Planktonics are very rare.

Age: The scrapings from the exterior represent Recent deposition. The age of the cavity fill is late Paleocene, from the P3 to P5 zonal interval, around 58–55 m.y. (Berggren, 1972), because the thinly-keeled morozovellids are restricted to this interval.

Environment: The few planktonic fossils suggest deposition in an open marine environment in low latitudes.

Station RC21/04-4

Hand specimens: Some dozen fragments up to 10×10×5 cm of whitish and blackish limestones, covered by Mn coating and by ahermatypic corals.

Samples 4A, B, E

Textures: Gray biomicrite to biomicroparite containing biosmata and bioclasts of amphisteginids, of

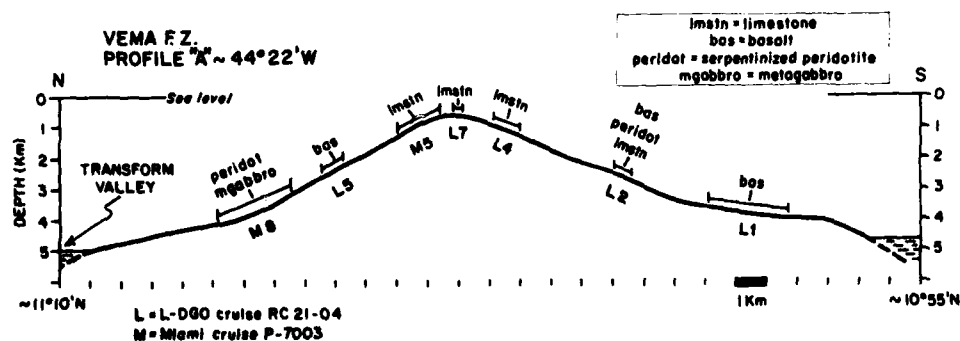


Fig. 3. North-south topographic profile (along section A in Fig. 1) across the shallowest part of the anomalous crustal block on the southern side of the Vema transform. No vertical exaggeration. Rock types recovered along this profile are indicated, including the limestones discussed in this paper.

TABLE 1

Rock samples obtained by dredging during L-DGO cruise RC21/04 from the transverse ridge on the southern side of the Vema transform zone, profile A in Fig. 3

Station	Description
RC 21/04-1 from: 10°37.0'N 44°23.65'W to: 10°40.95'N 44°25.0'W (4000 m–3650 m)	Deep part of south-facing slope of transverse ridge. Dredge haul. Weight ~ 25 kg. Basalt pebbles ~ 75%; Mn-coated semi-consolidated mud 25%
RC 21/04-2 from: 10°39.00'N 44°24.90'W to: 10°39.80'N 44°25.60'W (2750 m–2550 m)	Middle part of south-facing slope of transverse ridge. Weight ~ 40 kg. Basalt ~ 43%; dolerite 4%; volcanoclastics 43%; serpentinite breccia 3%; micritic red limestone 2%; "deep sea" limestone 5%
RC 21/04-4 from: 10°41.90'N 44°26.55'W to: 10°42.35'N 44°27.85'W (1400 m–1000 m)	Upper part of south-facing slope of transverse ridge. Weight ~ 80 kg. Various types of limestone, 100%
RC 21/04-5 from: 10°45.80'N 44°28.60'W to: 10°45.35'N 44°30.45'W (2650 m–2300 m)	Middle part of north-facing slope of transverse ridge. Weight ~ 3 kg. One freshly broken piece of diabase
RC 21/04-7 from: 10°43.05'N 44°28.45'W to: 10°43.15'N 44°28.80'W (650 m)	Summit of transverse ridge. Weight ~ 80 kg. Various types of limestone and corals, 100%

other large and small benthic foraminifera, of red algae, echinoids, and of rare corals, pelecypods, and planktonic foraminifera. Associated with this facies are variable amounts of reddish biomicrite containing often broken planktonic foraminifera (Fig. 5A, B).

Structures: The gray biomicrites are affected by complex networks of sedimentary dykes and cracks filled by the reddish biomicrites with planktonic foraminifera (Fig. 5C, D). In sample 4A the network is so irregular and widespread as to induce the complete brecciation of the rock. Dykes and cracks are irregular because they are conditioned by the porosity of the rock (see below). A few late borings, filled by serpulids and planktonic foraminifera in micrite, are also present.

The gray biomicrosparite contains several large vugs (up to 1 cm), which only in rare instances display a planar orientation, being usually irregular in shape and showing numerous roof and wall pendants (Fig.

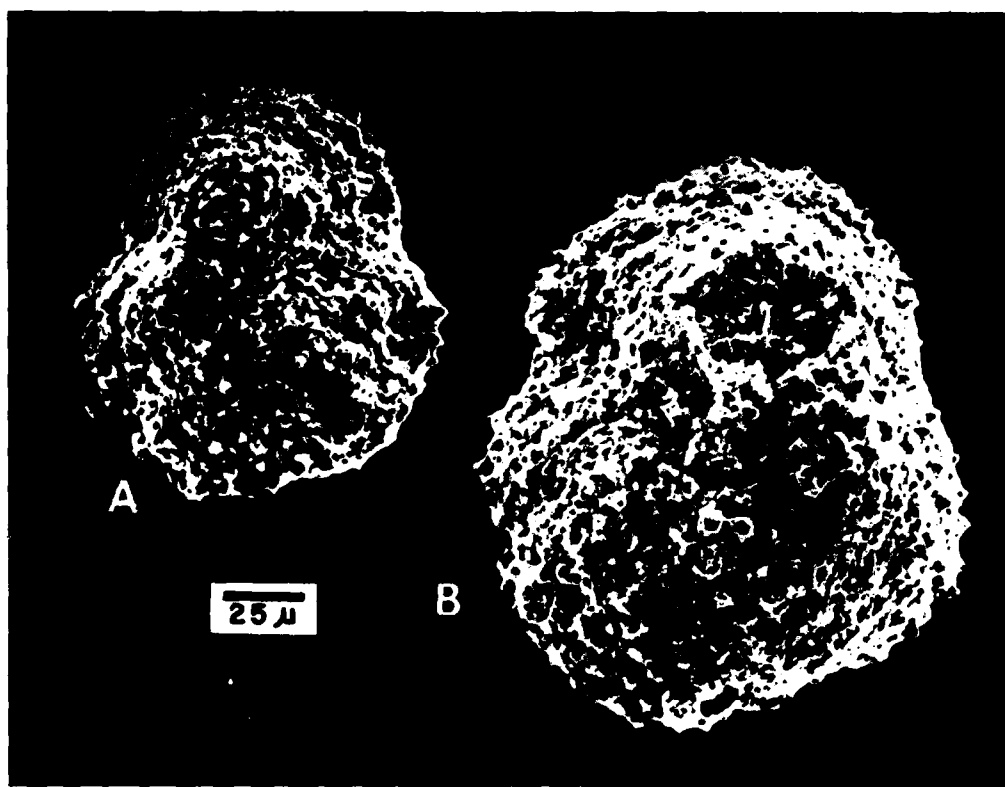


Fig. 4. Scanning electron micrographs of planktonic foraminifera resembling late Paleocene morozovellids, sample 2G. SEM pictures by Delia Brey.

6A). The vugs are often lined by radiaxial fibrous cement of calcite (Bathurst, 1972), although sometimes such cement is lacking or is substituted by a rim of limpid scalenohedral calcite (Fig. 6B). Many cavities contain geopetal fillings. The initial mechanical deposit, predating the fibrous cement, is rare and consists of almost barren red micrites or of peloidal silt bearing benthic foraminifera and possibly ostracodes. Radiaxial fibrous cement follows with a planar attitude at the bottom of the vug and with linings parallel to the irregularities of the remaining cavity. The subsequent mechanical deposit is abundant and includes red micrites bearing numerous broken tests of planktonic foraminifera. These fillings show at places (sample 4B) chaotic attitudes and vortices, mainly in the cavities lacking a cement lining. This late filling is probably related to the formation of cracks and dykes because in many cases a continuity between the red biomicrite of the dykes and that of the upper portion of the cavities is observed. Cracking postdates the development of the irregular cavities, so that dykes never display parallel walls but form instead a complex irregular network. Rapid filling of the cracks by the red biomicrite produced the vortices in the late fillings of the cavities and broke at places the linings of radiaxial fibrous mosaic. Other structures of the red biomicrite are only rare irregular cavities lined by scalenohedral limpid calcite.

XRD: Low-Mg calcite (1–3 mol% MgCO_3).

Foraminiferal fauna: The grey biomicrites contain a few fragments of planktonic foraminifera. In sample A there are no recognizable whole foraminiferal tests, though fragments of smaller benthic foraminifera are common. Samples B and E contain easily recognizable *Amphistegina* cf. *gibbosa* and a few smaller unidentified benthic forms; however, planktonic foraminifera are scarce and either fragmented or

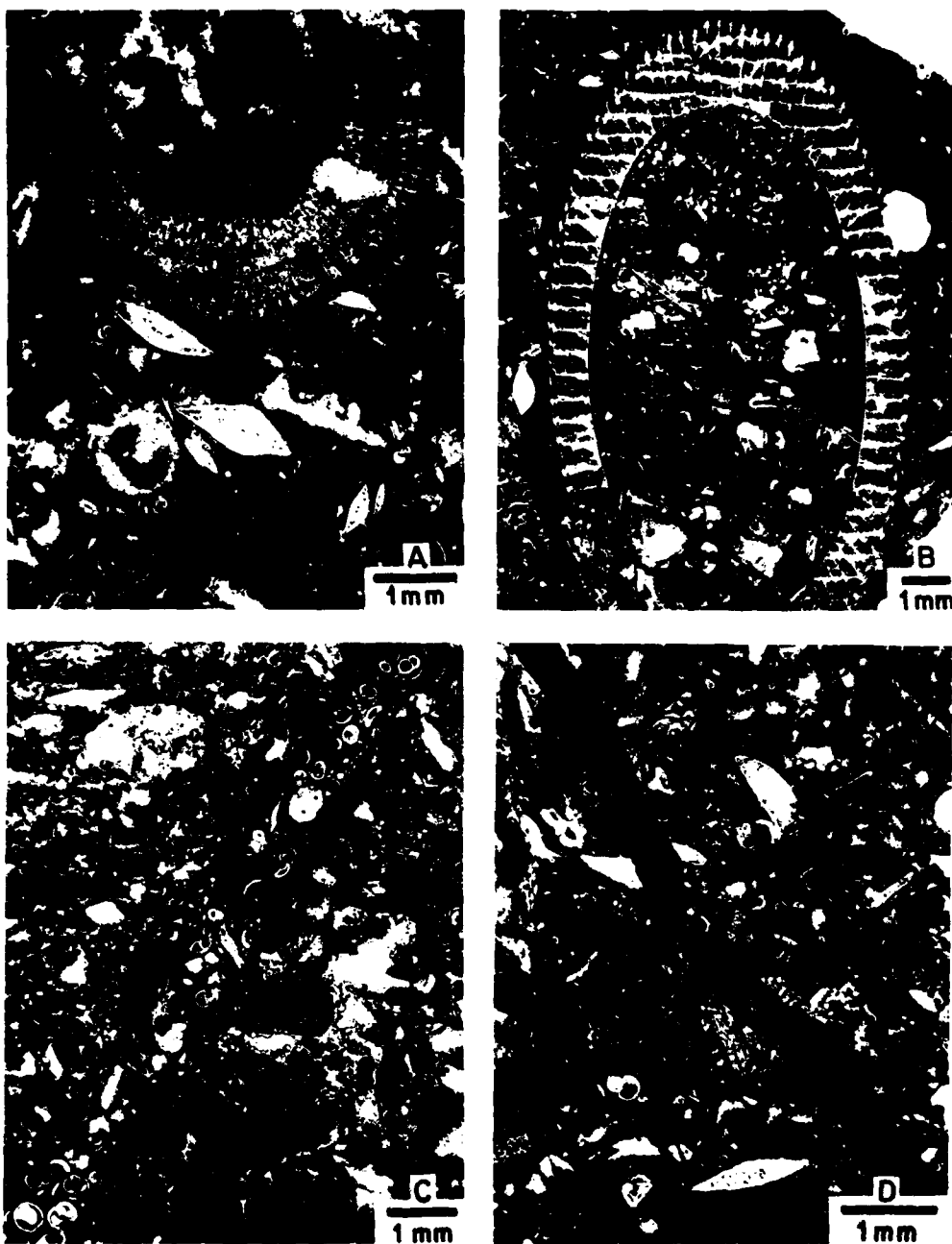


Fig. 5. Microphotographs (transmitted light) of thin sections of the limestones from the Vema Fracture Zone, illustrating some of the structures and textures discussed in the text.

A. Fossil association in sample 4a: red algae, amphisteginids, mollusks, benthic foraminifera and abundant fresh planktonic foraminifera.

B. Dark grey biomiorudite with abundant Fe-Mn hydroxide deposits and with a giant (~ 1 cm diameter) echinoid spine with geopetal infilling of test porosity. The different diagenesis of this bioclast suggests its reworking from shallower depths (sample 4b).

C. Regular dyke of Globigerina ooze within a limestone with no diagenetic vugs and porosity (sample 4d).

D. Dyke of Globigerina ooze cutting sharply across a well-lithified biomicritic limestone containing algae, amphisteginids and planktonic foraminifera (sample 7B2).

unrecognizable. Genera present are *Orbulina*, *Globigerinoides*, and *Globigerina*.

Age: These rocks contain few age-diagnostic species; however, the presence of *Orbulina universa* indicates that they are younger than Zone N9 (Berggren, 1972) of the middle Miocene.

Environment: The red algal- and amphisteginid-bearing gray biomicrite does not show evidence of reworking and must therefore have been deposited on a shallow carbonate bank, possibly adjacent to a reef, as indicated by the presence of corals. The maximum depth that these benthic communities can reach depends on the penetration of light in seawater and thus in turn on its transparency (Peres and Picard, 1964). For the central Atlantic a maximum depth of 100–150 m can be assumed. The associated planktonic foraminifera may have derived from surface currents impinging on this shallow topographic high, as is observed presently in several Pacific island reef environments (Bramlette et al., 1959; Todd and Low, 1960; Crouch and Poag, 1979).

Diagenesis: These subtidal limestones were affected by early diagenetic processes in an intra-supra-tidal vadose environment. This led to:

(a) formation of the vugs, first by desiccation shrinkage (Shinn, 1968) but mainly by chemical leaching (Castellarin and Sartori, 1973), as suggested by the scarce planar orientations of the vugs by their irregularity;

(b) deposition inside the cavities of possible subaerial deposits (red barren micrites);

(c) precipitation of linings of early acicular cement, lately substituted by radial fibrous mosaic of calcite cement (Kendall and Tucker, 1973);

(d) change in mineralogy from previous high-Mg calcite (benthic foraminifera, red algal molds) and aragonite (corals and pelecypods, in part) to the present low-Mg calcite. This process could, however, have occurred later.

Emergence of the shallow carbonate bank was followed by drowning of the site accompanied by tensional cracking and fissuring of the porous and early consolidated rocks. Red biomicrites with planktonic foraminifera entered the tensional cracks and the early diagenetic vugs, rapidly and sometimes with chaoticization. Cracks are irregular because the rock had already developed a widespread porosity.

Samples 4a, b, and D

—Sample 4a:

Texture: Gray biomicrite with biosomata and bioclasts of red algae, molluscs, corals, amphisteginids and other benthic foraminifera; the amphisteginids are fresh. Abundant planktonic foraminiferal tests are lined by internal fringes of acicular cement and sometimes filled by sparite monocrysts. In one case there is a geopetal filling with the lower half of the test filled by micrite and the upper part by two generations of cement.

Structures: Roundish cavities filled by red, consolidated foraminiferal ooze, sometimes with peripheral rims of microspar cement inside these pelagic fillings. These are interpreted as boring fillings.

—Sample 4b:

Texture: Gray biomicrudite containing echinoids with very large spines, more than 1 cm in length, but no overgrowths. Other fossils include red algae, internal molds of gastropods (the shell having been completely leached), amphisteginids, and fresh and relatively abundant planktonic foraminifera. A very few leached corals were observed. The rock also contains diffused Fe–Mn oxides, which are often dendritic and fill the dissolution cavities of former shells. Bioclasts are packed, often fragmented with subrounded edges.

Structure: No borings are evident. The main structure is the porosity induced by the dissolution of aragonite shells.

—Sample 4D:

Texture: Biomicrite with amphisteginids, small benthic foraminifera, a few echinoids, red algae, a coral fragment, bioclasts and biosomata of a *Miogypsinoidea*-like taxon, and several benthic foraminifera with reddish shells, possibly miliolids. Planktonic foraminifera are relatively common and fresh. Most bioclasts are well rounded and lack mechanical abrasions.

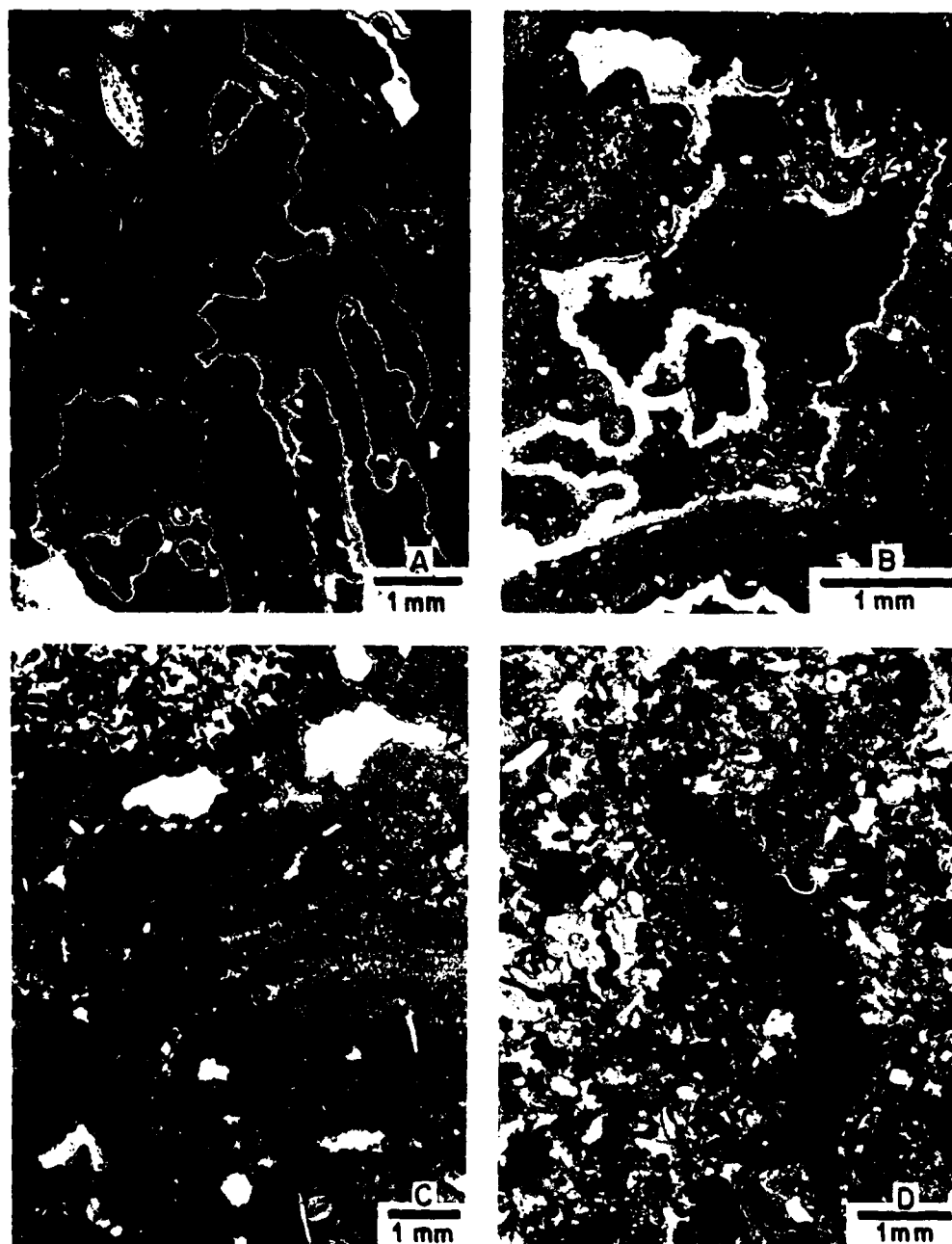


Fig. 6. Continued from Fig. 5.

A. Irregular vugs in shallow-water biomicrite deriving probably by chemical leaching on pre-existing possibly planar vugs produced by dessication shrinkage, and suggesting inter-supratidal diagenesis. Note that the walls and pendants are lined by radiaxial fibrous mosaics, with typical scalloped patterns of micritic inclusions. Note also that in a few cases a mechanical filling, black and barren, possibly of

Structure: Two large dykes with straight and parallel walls are filled with bioclasts and biosomata of planktonic foraminifera in a red micritic matrix.

XRD: Low-Mg calcite (1–3 mol% MgCO_3).

Foraminiferal fauna: Foraminifera outside the dykes are not common, and not easily recognizable. *Orbulina universa* is the only unequivocal identification made. Within the dykes foraminifera are very common and many are whole. Species include *Globorotalia miocenica*, *Sphaeroidinellopsis* spp., and *Orbulina universa*. *Amphistegina* cf. *gibbosa* is common in the gray biomicrite.

Age: The outside biomicrite containing *Orbulina* is younger than middle Miocene Zone N9 (Berggren, 1972), that is, younger than 14 m.y. The dyke fillings, however, contain species typical of the early Pliocene zone N19–20, or about 5–3 m.y.

Environment: The rock components are the same found in other samples from Station 4, so that we can assume a depth of formation of less than 100–150 m, probably of only a few meters, at which depth the large echinoid spines are commonly found. However, textural characters such as the richness and freshness of planktonic foraminifera and the clastic, roundish appearance of many clasts, suggest that these samples represent penecontemporaneous products deposited downslope of the carbonate bank represented in the other samples from Station 4.

Diagenesis: Early diagenetic processes are not so severe as they are in the previous samples from Station 4. They include dissolution of aragonite shells and rare geopetal intragranular cavities.

Station RC21/04-7

Hand specimens: A number of large fragments of biogenous limestones, partly covered by black Mn-oxide coatings.

Sample 7C

Textures and structures: A large (40 × 30 × 20 cm) fragment of coral, with one surface freshly cut and the opposite one black, very rough, and irregularly bored and pitted.

Age: Dr. J.W. Wells of Cornell University identified this specimen as a hermatypic coral of the genus *Porites*. The genus ranges from the Eocene to the Recent, and is particularly common in the Miocene. A species name could not be assigned due to the preservation state of the specimen.

Environment: A reefal environment, probably less than 20 m in depth, is indicated by the relatively large size of the colony of which this specimen is only a small bit.

Diagenesis: The bored and pitted black surface may derive in part from Mn hydroxide deposition and submarine borings, but also recalls macroscopic alteration of coral reefs in the intertidal zone, such as at Soldier Key, Florida.

Samples 7A, B, B2, B3

—Sample 7A:

Texture: A large (6 × 6 cm) rhodolite (Bosellini and Ginsburg, 1971), that is, a rounded algal ball (Fig. 6C) made of thallia of red algae (*Lithothamnium* and/or *Lithophilum*) in micrite, containing molluscs, other

subaerial origin, can be observed underneath the early cement. Note also internal fillings of *Globigerina* ooze, often chaoticized and with vortices (sample 4b).

B. Irregular rim vug lined by radiaxial fibrous mosaic (replacement of an earlier acicular cement) and different generations of mechanical fillings of *Globigerina* ooze (sample 4e).

C. Portion of Rhodolite (nodule of red algae) with laminae growing around the nucleus (upper part of picture) and including also small amphisteginids in the lower right (sample 7).

D. Moulds of dissolved aragonite bioclast (mollusk) filled by Fe–Mn hydroxide deposit. Previous high-Mg calcite fragments (as of red algae) are not dissolved but have changed into low-Mg calcite (sample 7B3).

red algae, amphisteginids, and rare planktonic foraminifera. Echinoids are rare. The core of the rhodolite is made of a hermatypic coral fragment, the laminae contain a few amphisteginids.

Structure: There are overgrowths on the echinoid fragments; amphisteginids and planktonic foraminifera appear somewhat recrystallized, with edges made up of radially-arrayed scalenohedral calcite. Shell edges are not sharp. Some intralaminar cavities of the rhodolite have a lining of palisade crystals. A few borings are present.

—Sample 7B:

Texture: Algal balls and other fragments of Rhodiferae, molluscs, echinoids, amphisteginids, and scarce plankton. The matrix is very fine micrite, almost barrén, very dense and reddish to blackish, suggesting an abundance of organic matter.

Structure: Echinoids do not show overgrowths, but only occasional palisade rims. Planktonics and amphisteginids are fresh and not recrystallized. Some borings are filled by red pelagic micrite containing planktonic foraminifera.

—Sample 7B2:

Texture: There are fragments of red algae, amphisteginids, echinoids, molluscs, and barely distinguishable, very rare planktonic foraminifera in a light grey, very fine and homogeneous micrite. There is a zone of brecciation including fragments of manganese hydroxides and dykes and patches containing red pelagic micrite with planktonic foraminifera.

Structure: Apart from brecciation, there are echinoids with overgrowths. Amphisteginids are very poorly preserved, and have marginal radial scalenohedral calcite crystals.

—Sample 7B3:

Texture: Large, well rounded colonies of red algae, fragments of amphisteginids, pelecypods, echinoids, and rare planktonic foraminifera in scarce micrite.

Structures: Echinoids display overgrowths; amphisteginids are poorly preserved and with a peripheral rim of scalenohedral calcite (sometimes present also in planktonic tests). There are also numerous cavities without cement linings but with mechanical deposits. The vugs are sometimes rounded, more often extremely irregular, usually with smooth rims. Earliest fillings look like crystal silt, as found in the vadose environment (Dunham, 1969); others contain rare, undetermined shells. These fillings have often a gradational contact with a dense, blackish micrite containing a few planktonic foraminifera. Fragments of aragonitic shells dissolved and replaced by Mn hydroxide were observed (Fig. 6D).

XRD: Low-Mg calcite (3 mol% MgCO_3).

Foraminiferal fauna: Included in the patches of homogeneous matrix are *Globigerinoides trilobus*, *Globigerinoides ruber*, *Globigerina bulloides*, *Orbulina universa*, *Sphaeroidinella* sp., and possibly *Globoquadrina altispira*. *Amphistegina* cf. *gibbosa* is the most common benthic foraminifer.

Age: The coexistence of *Sphaeroidinella*, probably *S. dehiscens*, and *Globoquadrina altispira*, suggests that these samples are mid-Pliocene in age, Zone N19 (Berggren, 1972) about 3 m.y. old.

Environment: Algal balls live typically in water with intense currents within the photic zone (less than 150 m), that is, on submarine highs or intertidal channels in lagoons. This fits with the scarcity of micrite and the ruditic aspect of many samples. The direct association with hermatypic corals, the scarceness of planktonic foraminifera, and the presence of patches of dense micrite suggest a back-reef environment or a fore-reef terrace. Alternatively, the algal balls may have been reworked. An environment of a quiet, sheltered lagoon can be envisaged for sample 7B, with no signs of reworking or of strong water dynamics, but with a dense micrite rich in organic matter and devoid of planktonic foraminifera.

Diagenesis: The observed structures point to moderate early vadose diagenesis for samples 7A, B2, B3 (geopetal cavities, crystal silt-like deposits, leaching, etc.). Sample 7B lacks any evidence of inter-supratidal diagenesis.

DISCUSSION

That the anomalous topographic high on the southern side of the Vema transform is not a constructional volcanic feature was already suggested by Van Andel et al. (1967) and confirmed by Bonatti and Honnorez (1971). Lithology (Van Andel et al., 1971) and gravity and magnetics (Robb and Kane, 1975) suggest we are dealing with an uplifted block of crust and upper mantle.

The information concerning environment of deposition, age, and post-depositional diagenesis of the limestones recovered from the uplifted block (summarized in Table II), can be interpreted in terms of vertical motions relative to sea level of the crustal block itself, as follows:

(A) Lithofacies analysis of limestones obtained from the summit of the transverse ridge (Station L-7 on profile A, Fig. 3) indicates that these samples were deposited close to sea level in middle Pliocene time, i.e., about 3 m.y. before the present. Some of these samples show evidence of subaerial exposure. Subsequent subsidence of the summit of the transverse ridge down to its present level (~ 600 m below sea level) gives an average subsidence rate of 0.2–0.3 mm/year. The estimate does not take into account possible eustatic sea level variations in the Pliocene, which, in any case, did not exceed 50–100 m at most.

If we assume that the anomalous crustal block was originally created at the southeastern MAR axial segment, located presently about 360 km to the east, and if we adopt a spreading rate of 1.1–1.2 cm/year, extrapolated from profiles made immediately to the north of the Vema transform by Van Andel et al. (1971) and Bonatti and Honnorez (1976), the age of the crustal zone of the anomalous block is roughly 35 m.y. Subsidence rate predicted by the thermal contraction model for Atlantic crust of this age should be on the order of 0.01 mm/year (Sclater et al., 1971; Trehu, 1975). Thus, the average subsidence rate of the anomalous crustal block during the last 3 m.y. exceeds the subsidence predicted by the thermal contraction model by over one order of magnitude.

(B) Limestones from the upper part of the slope on the transverse ridge's southern side (Station 4 on profile A, Fig. 3) give evidence of formation close to sea level in mid to late Miocene time, between 5 and 14 m.y. before present. They also show evidence of subaerial exposure. Subsidence down to their present depth (1000–1400 m below sea level) gives a minimum average subsidence rate of 0.1–0.3 mm/year, in agreement with the rate estimated for samples of Station 7 on the crest (Fig. 7). Given that these mid to late Miocene limestones outcropping several hundred meters below the crest of the anomalous block were deposited close to sea level, and assuming that the morphology of the crustal block did not change significantly, it follows that the crest of the block reached a few hundred meters above sea level in mid to late Miocene time. Alternatively, it is possible that upward growth of the calcareous reef during subsidence from mid to late Miocene to mid Pliocene time kept the crest of the crustal block close to sea level throughout this time interval.

TABLE II
Summary of results of study of limestones recovered from three stations on crustal block on south side of Vema transform—L-DGO cruise RC 21-04

Sample	Present position	Environment and age of formation	Postdepositional history
7A	Summit of the transverse ridge ~ 650 m below sea level	Shallow (< 40 m) back-reef lagoon in calcareous bank Middle Pliocene (~ 3 m.y.)	Subaerial diagenesis in samples 7C and 7D Subsidence at average rate $\geq 0.2-0.3$ mm/year from ~ 3 m.y. ago to present
7B			
7C			
7D			
4A	Upper part of transverse ridge slope, 1000-1400 m below sea level	Shallow (< 40 m) back-reef lagoon in calcareous bank Middle to upper Miocene (~ 10-6 m.y.)	Subaerial diagenesis in samples 4A, B, E Subsidence at average rate $\geq 0.1-0.3$ mm/year from ~ 10-6 m.y. ago to present
4B			
4E			
4a			
4b	Middle part of transverse ridge slope 2550-2750 m below sea level	Bathyal sea floor on topographic high; lower Miocene (~ 23-18 m.y.) for samples 2, 2D, 2H Open marine; late Paleocene (58-55 m.y.) for sample 2G	Uplift from lower Miocene to middle-upper Miocene; then subsidence to present level Old (late Paleocene) sediment left on presumably younger (~ 35 m.y.) crust
4D			
2			
2D			
2H			
2G			

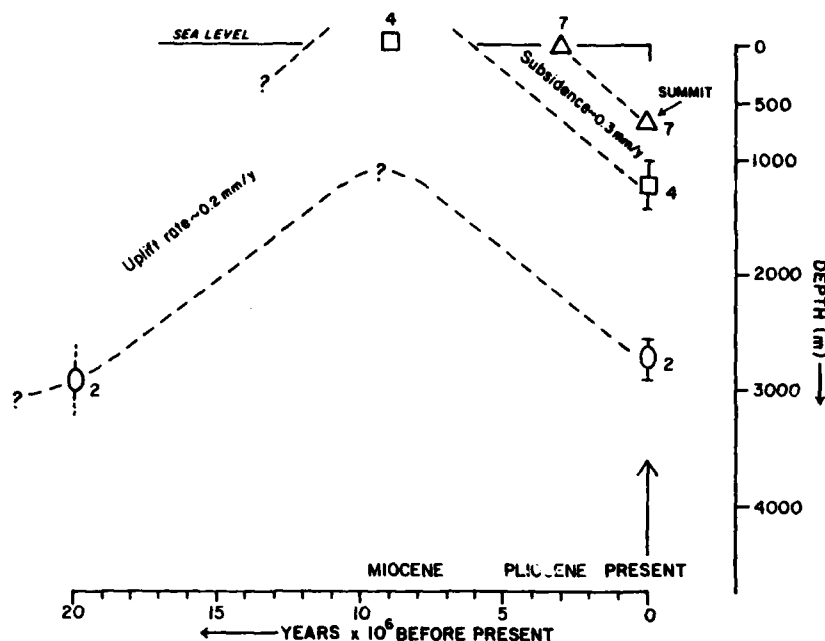


Fig. 7. Schematic interpretation of Miocene-Pliocene movements of the crustal block on the southern side of the Vema transform, based on the study of limestones recovered at three different levels on the uplifted block.

Determination of the thickness of the limestone cap by seismic methods and by close-spaced sampling may settle this matter.

(C) On Section A (Fig. 2) parallel to and on the southern side of the transform valley, we see that the sea floor becomes anomalously shallow about 200 km away from the axial accreting segment of the Mid-Atlantic Ridge, with the shallowest point (about ~ 600 m) reached about 360 km from the axis. If we were to assume a similar topography in the past and steady sea floor spreading at about 1.1 cm/year, we could estimate a rate of uplift of about 0.2 mm/year. The steady state assumption upon which this estimate is based is surely affected by significant uncertainties and errors, one being that the crest of the anomalous block was at sea level 3 m.y. ago and is ~ -600 m deep presently. Even so, 0.2 mm/year might represent an order of magnitude estimate. This rate of uplift is similar to the rate of subsidence estimated for the anomalous block since the middle Pliocene (about 3 m.y. ago).

(D) Limestones recovered from 1550 to 1750 m below sea level on the middle part of the southern slope of the transverse ridge (Station 2, Fig. 3) give ages of early Miocene (near 23-18 m.y.) and late Paleocene (58-55 m.y.). Faunas suggest deposition in the bathyal zone in the early Miocene and possibly deeper in the Paleocene.

The presence of late Paleocene (58-55 m.y.) sediments suggests that crustal material that age or older is present on the uplifted crustal block. Even assuming the low average spreading rate of ~ 1.1 cm/year, the crust on the southern side of the

Vema transform along Section A (Fig. 1) where the limestones were recovered should not be older than about 35 m.y. Thus, a problem exists in reconciling the maximum age of ~ 35 m.y. predicted for a spreading crust, with the presence of material 58–55 m.y. old. This problem is compounded if we consider previous findings of a limestone possibly as old as Cretaceous on the uplifted crustal block (Bonatti and Honnorez, 1971; Honnorez et al., 1975). Simple mechanisms permitting old crustal blocks to be left behind in the transform domain during spreading are hard to envisage, though some have been discussed as possibilities (Bonatti, 1973; Bonatti and Crane, 1982).

(E) Possible factors which may determine vertical tectonic movements of crustal and upper mantle blocks near oceanic transform/fracture zones have been discussed previously (Bonatti, 1978). These possible factors are: (a) lateral conduction of heat across the transform close to its intersections with accreting ridge segments; (b) viscodynamic forces operating close to the intersection of the transform with the accreting ridge (Sleep and Biehler, 1970; Van Andel et al., 1971); and (c) zones of compression and extension which may develop along fracture zones due to small changes in direction of spreading, to non straight transform boundaries, and to the horizontal component of thermal contraction. Bonatti (1978) estimated that factors (c) above are generally the most important.

It has been suggested that a change in pole of rotation and readjustment in direction of spreading occurred in the vicinity of the Vema Fracture Zone about 10 m.y. ago (Van Andel et al., 1971). According to this suggestion the Vema transform has undergone, since that time, slight extension in a direction perpendicular to the strike of the transform. We have shown (Fig. 7) that the crustal block on the southern side of the Vema transform was around 10 m.y. ago in a phase of maximal vertical uplift, and that it subsequently started to subside. It is possible that the subsidence is related to the extensional regime postulated to prevail at the Vema transform in the last 10 m.y., and that uplift occurred during a preceding period of a prevailing compressional regime related to a different pole of rotation for crustal motions in the central north Atlantic. We will not speculate further at this stage on the causes of vertical movements of the Vema uplifted crustal block. More precise models will have to await additional data on rates and ages for these vertical motions. An explanation for the anomalously old uplifted crust found at the Vema Transform, involving reorientation and migration of the transform, has been proposed recently by Bonatti and Crane (1982).

(F) Similar vertical tectonism as that documented for the Vema Fracture Zone has been reported for the Romanche Transform Zone at the equator in the Atlantic (Bonatti et al., 1977; Bonatti and Chermak, 1981). A several hundred km-long slice of crust on the northern side of the Romanche Transform is anomalously shallow by as much as 3 km relative to the level predicted by the lithospheric thermal contraction model. The crest of this uplifted crust was at or above sea level at the Miocene/Pliocene boundary (about 5 m.y. ago) and subsided since at an average

rate one order of magnitude faster than subsidence due to "normal" cooling of the lithosphere (Sclater et al., 1971; Trehu, 1975). Whether vertical tectonic motions at the Vema and Romanche can both be related to general events caused by plate movements in the central/north Atlantic, or whether each transform acted independently of the other as far as vertical tectonism, are questions which require more work to be answered.

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